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Evaluation of energy consumption and CO_2 emissions of electric city buses

(Title in earlier provisional programme: Evaluation of hybrid and electric powertrains in mobile machinery. Roadmap work on electrifying mobile machines with VTT, LUT, & Aalto)

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ECV seminar on May 11-12, 2016, Helsinki, Finland

ECV @ Aalto University

Tubridi: full-scale series hybrid mining loader

eBus: electrical bus, electrical bus system

eStorage: battery testing and virtual battery

→ Design & construction electrical powertrains

→ Future perspectives (e.g. the roadmap work with partners)

→ 4 doctoral, 2 licenciate, 22+ master theses, 30+ publications

→ Reflected to new projects, numerous student projects

Content

Breakdown analysis of energy consumption and carbon dioxide emissions for two electric city bus concepts

Different primary energy pathways for electricity are analysed in terms of energy efficiency and emissions

The energy losses for charging and bus operation are evaluated based on the simulations carried out by vehicle simulation

Under different driving cycles and ambient conditions

Well-to-tank (WTT) or well-to-pump (WTP) energy efficiency and carbon dioxide (CO_2) emissions in electrical power production

Electricity produced from fossil sources CO_2: 150…300 g/MJ

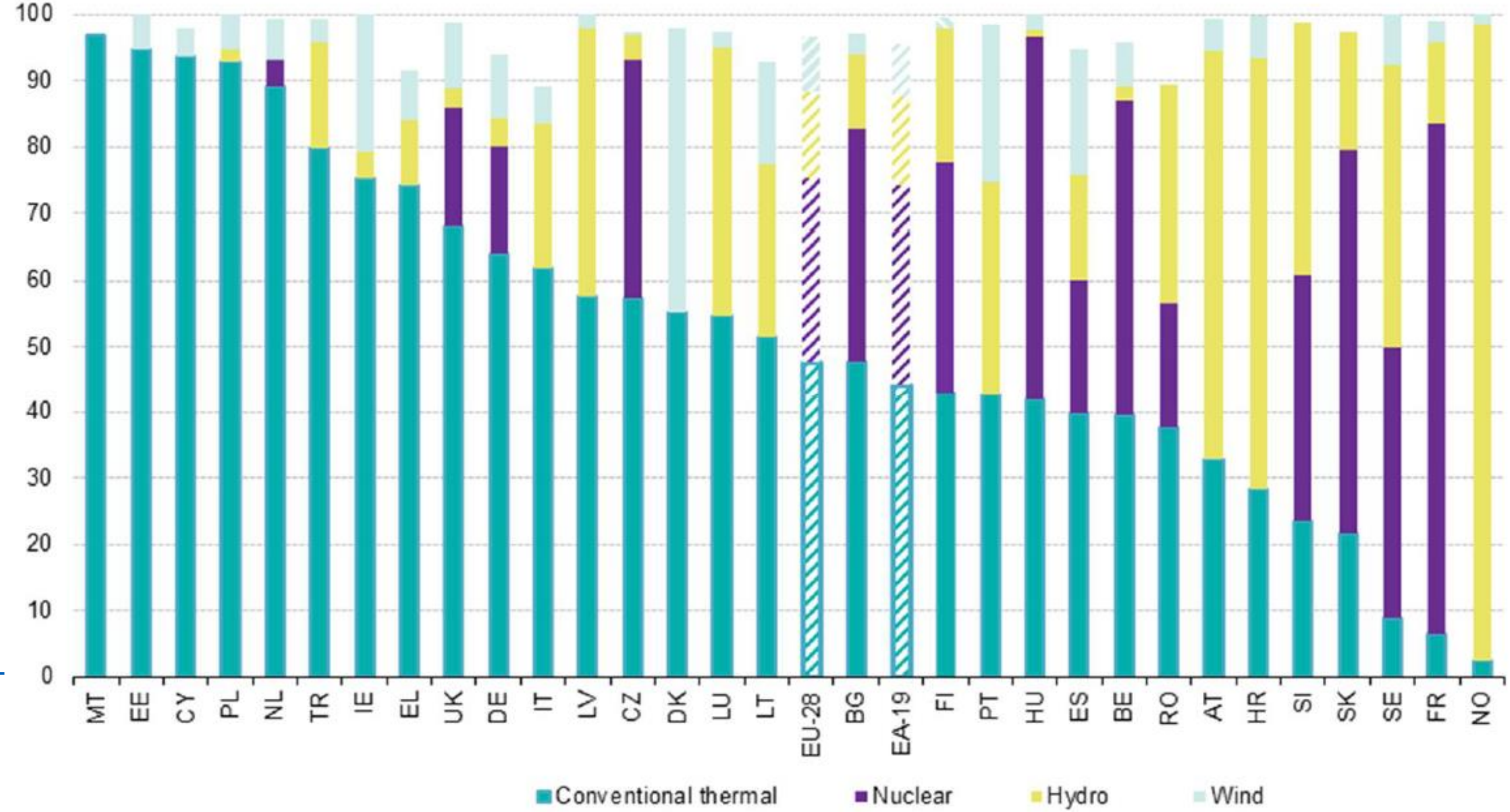
When defining CO_2 emissions of vehicles, emission values of electricity grid mix are often used

In average European mix CO_2: 104.5…138.0 g/MJ

Finnish average 2015, CO_2: 32.8 g/MJ

Numbers vary in different studies, tendency is to decrease

Breakdown of electricity production by source in EU-28 countries (according to Eurostat)



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Energy production pathways

Pathway	Description	Expended energy (MJ/MJ_{fuel})	GHG emissions ($g\ CO_{2eq}/MJ_{fuel}$)
EMEL1	EU-mix (high voltage)	1.94	135.99
EMEL2	EU-mix (medium voltage)	2.05	141.13
EMEL3	EU-mix (low voltage)	2.24	150.11
KOEL1	Coal (hard), conventional	1.81	292.37
KOEL2	Coal (hard), IGCC[1]	1.54	262.36
KOEL2C	Coal (hard), IGCC + CCS[2]	1.98	71.04
GPEL1a	NG, pipe 7000 km, CCGT[3]	1.35	144.98
GPEL1b	NG, pipe 4000 km, CCGT	1.19	132.43
GPEL1bC	NG, pipe 4000 km, CCGT, CCS	1.71	44.67
GREL1	LNG, CCGT	1.39	141.62
NUEL	Nuclear	2.40	0.39
WDEL	Wind	0.12	0.00
FIMIX	Electricity grid mix in Finland	1.43	32.8

1) Integrated Gasification and Combined Cycle, 2) CO_2 Capture and Storage, 3) Combined Cycle Gas Turbine

Load cycles examined

Espoo 11 (E11), H550, Line 51B (L51B) measured cycles including elevation profiles

Helsinki (H3) is an extra-urban reference cycle

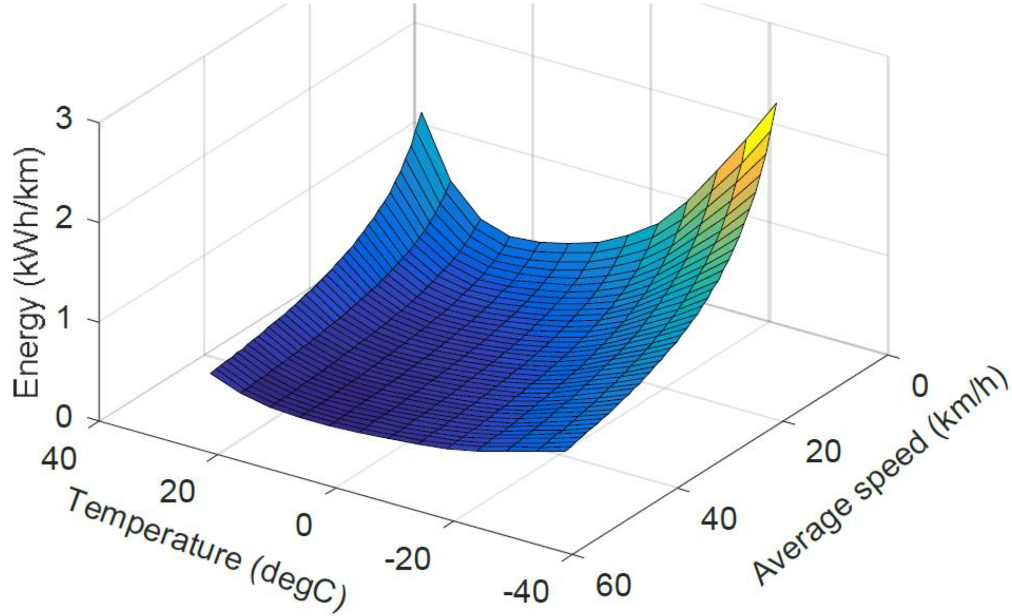
Braunschweig (BR), Manhattan (MAN) common reference cycles

Number of buses based on 10 interval in route

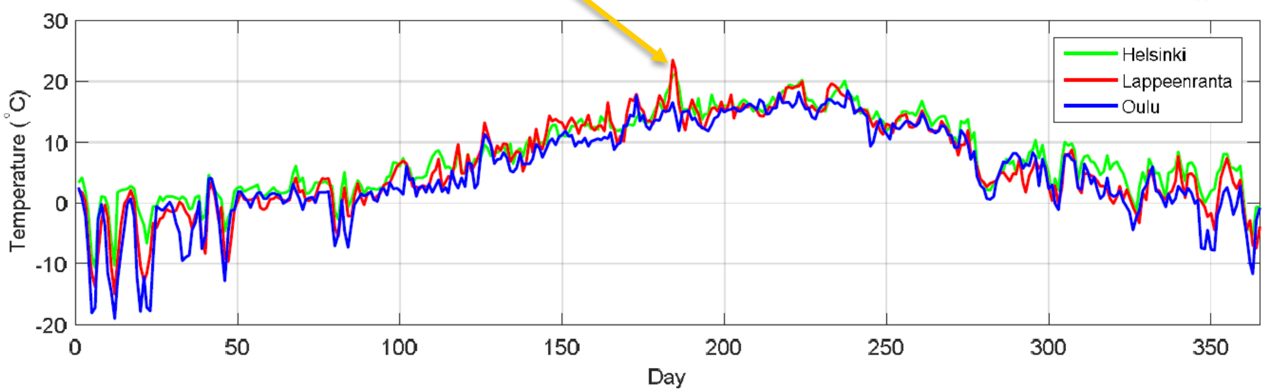
	BR	E11	H550	H3	L51B	MAN
Time (s)	1740	1548	3384	902	4283	1089
Distance (km)	10.9	10.2	28.7	10.3	16.1	3.3
Maximum speed (km/h)	58.2	58.4	74.9	71.7	59.0	40.5
Average total speed (km/h)	22.5	23.8	30.5	41.2	13.6	10.9
Average speed (km/h)	30.1	27.9	36.0	48.4	20.2	17.1
Stops per km	2.7	1.8	1.3	0.9	4.3	6.1
Aggressiveness (m/s^2)	0.235	0.152	0.206	0.195	0.281	0.306
Climbing gradient (m/km)	0.00	5.75	6.80	0.00	7.27	0.00
Descending gradient (m/km)	0.00	-5.83	-6.64	0.00	-7.26	0.00
Number of buses in a fleet	7	7	13	5	16	5

Environment

The auxiliary power consumption was based ambient temperature



SUMMER!



Busses examined

Two types of battery electric city buses were analysed:

- EV1: opportunity charging (battery 77 kWh)
- EV2: overnight charging (battery 373 kWh)

Energy consumption and CO_2 emissions in terms of:

- Powertrain, driving cycle, ambient conditions (temperature) and passenger load

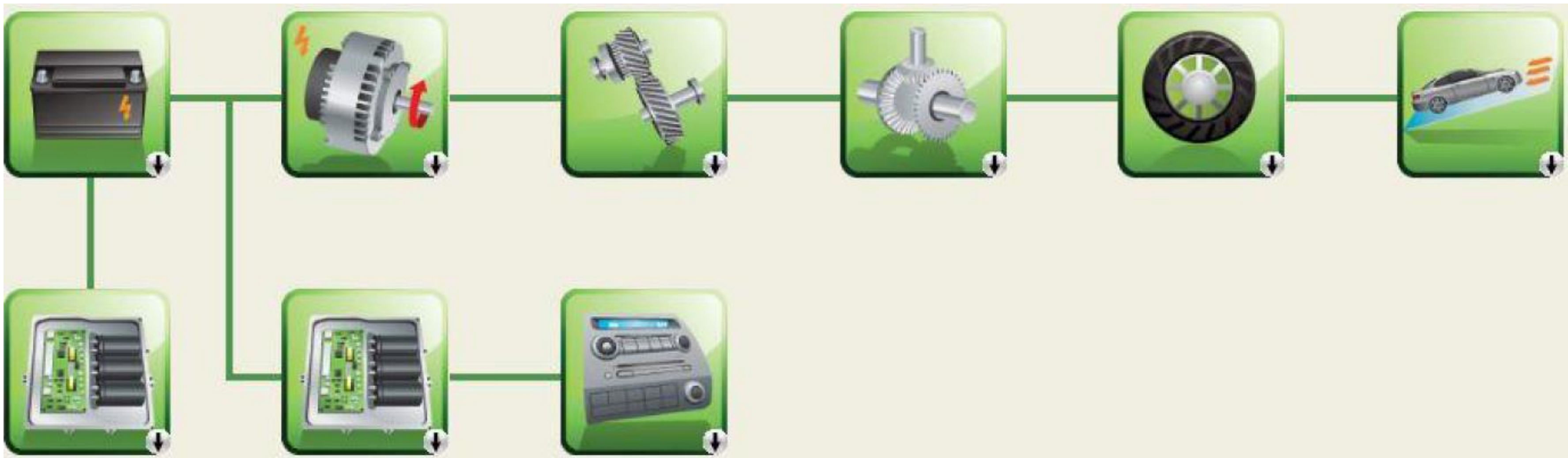
Total energy consumption and CO_2 emissions were calculated for different driving cycles

Bus configuration

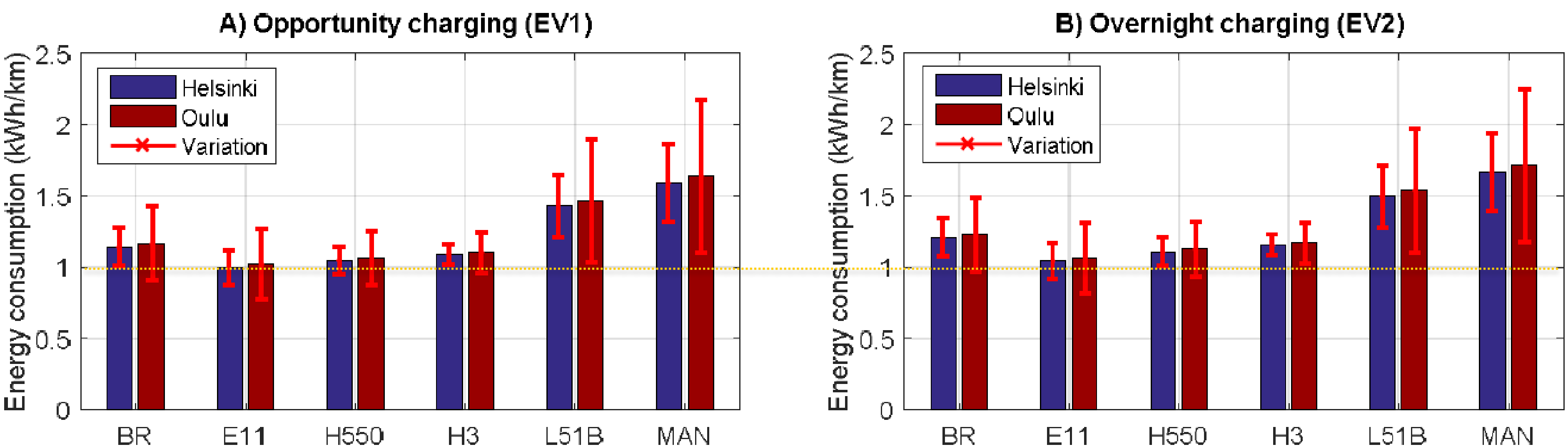
Configuration	EV1 (opportunity)	EV2 (overnight)
Battery chemistry and capacity	Titanate Oxide, 60Ah	Graphite/NMC, 200Ah
Battery cell specific energy (Wh/kg)	80	160
Battery module configuration	10 cells in series	7 cells in series
Battery pack configuration	8 modules: 4 in series, 2 in parallel	6 modules: 2 in series, 3 in parallel
Battery system configuration	7 pack in series	12 pack in series
Battery system specific energy (Wh/kg)	60	120
Battery capacity (kWh)	77.3	373.0
Battery system weight (kg)	1295	3106
Motor nominal power (kW)	170	170
Motor max peak torque (Nm)	1710	1710
Gear reduction	1.75	1.75
Final drive ratio	4.72	4.72
Tires	275/70/22.5	275/70/22.5
Bus curb weight (kg)	10795	12606
Load capacity mass (kg) / persons	7205 / 96	5394 / 72
Charging efficiency	0.82	0.87
Battery depth of discharge	0.75	0.9
Operating hours in a year	4000	Cycle dependent

Simulation model

Realised in Autonomie software



Results 1: Annual average energy consumptions



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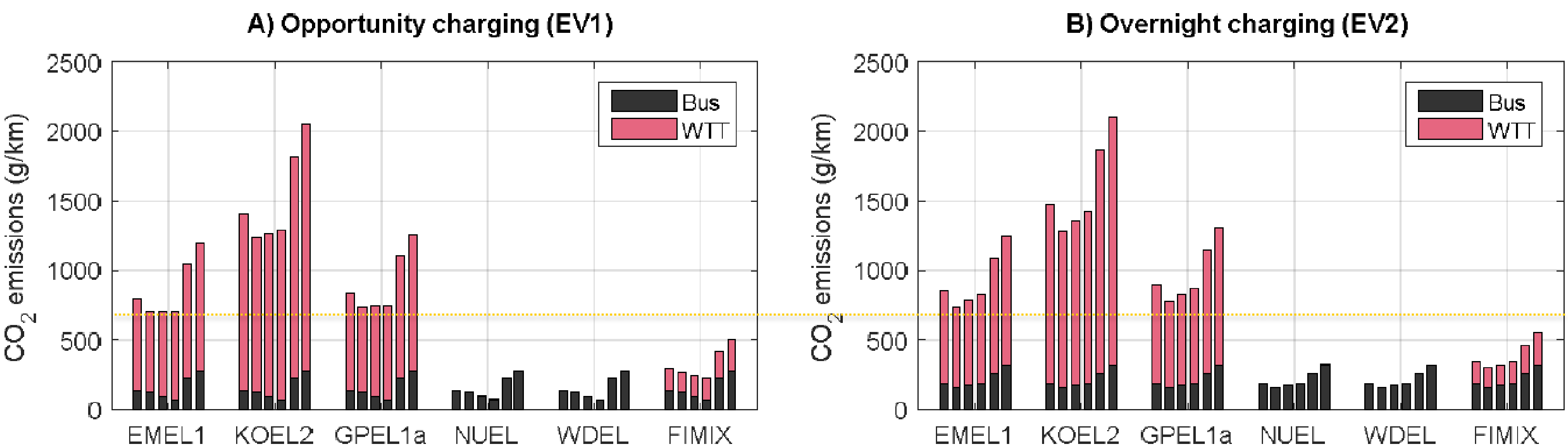
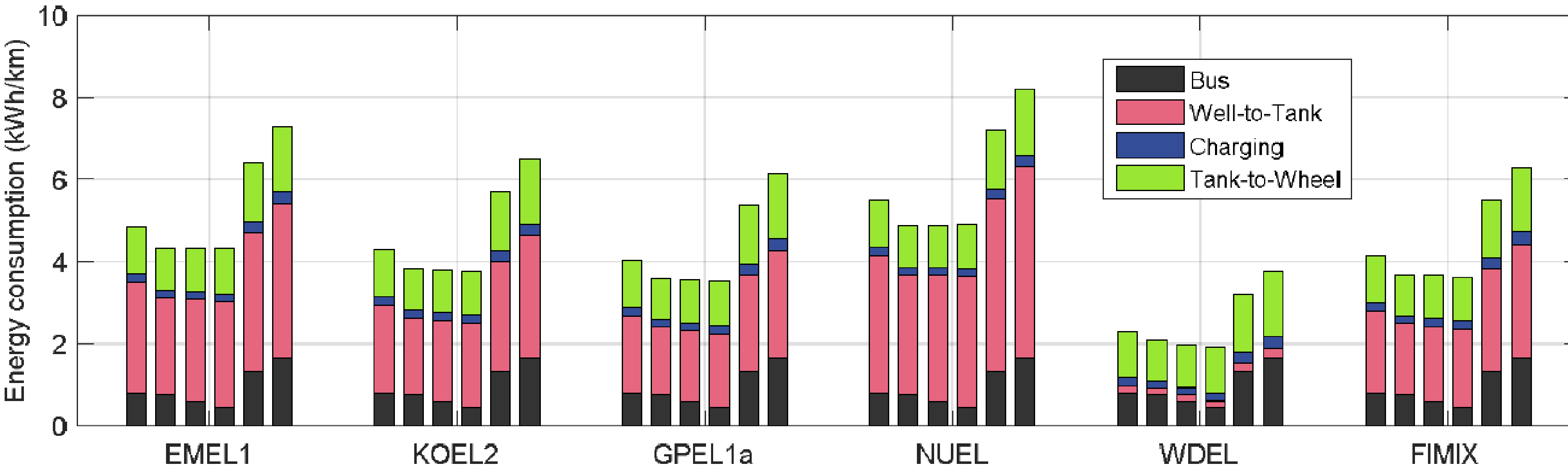
Results 2: Carbon dioxide emissions from the bus manufacturing and electricity generation



Results 3: Total energy consumption distribution: different phases of bus lifecycle (EV2)



Conclusions 1: Pathway matters

Primary energy sources (pathways) influence on global energy efficiency and CO2 emissions of electric vehicles

Electrical energy pathway has crucial role as no local emissions exist

The energy consumed in electricity production was higher for the fossil fuel based pathways whereas it was very low for the wind energy pathway

→ Finnish (and Scandinavian) grid mix make offer grounds for EVs

For CO2 intensive pathways: Well-to-Wheel phase is multiple times higher than bus manufacturing CO2

[Conclusions 2: EV technology]

Ambient temperature had influence of about 10 % on energy consumption (at both extremes, more in cold side in our climate)

Significant differences in distance specific energy consumption exist between different operation routes

Passenger load and driving style had important influence on energy consumption

In higher speed cycles, annual distance is higher → higher amount of total energy per year